International Journal of Mechanical and Production Engineering Research and Development (IJMPERD)
ISSN (P): 2249-6890; ISSN (E): 2249-8001
Vol. 9, Issue 3, Jun 2019, 1625-1634

TURBOGENERATOR: DESIGNING AND LAYOUT DEVELOPMENT

N. A. KHRIPACH, D. A. IVANOV, A. P. TATARNIKOV & B. A. PAPKIN

Moscow Polytechnic University, Bolshaya Semenovskaya Street, Moscow, Russia

ABSTRACT

This article discusses the development of turbogenerator model intended for energy units of small scale and distributed power generation. Turbogenerator model should be developed on the basis of computational fluid dynamics, which permits to adjust model design and to determine variables of the cooling system which provides required temperature mode during operation of electric machine. Test results of two variants of turbogenerator model are presented which were analyzed from the point of view of reasonability (operability) of the adopted technical solutions. Based on the analysis of the two variants of turbogenerator, model optimum variables of the developed design were selected and used for its fabrication. Appropriate conclusions have been made with respect to main trends and properties.

KEYWORDS: Turbogenerator, Simulation, Computational Fluid Dynamics, Turbine Wheel & Cooling System

Received: Apr 07, 2019; **Accepted**: Apr 27, 2019; **Published**: Jun 12, 2019; **Paper Id**.: IJMPERDJUN2019171

Original Article

1. INTRODUCTION

Nowadays application of heat recovery systems attracts great attention due to price increase of energy sources, advances in energy saving technologies and constraints of harmful emissions with exhaust gases (EG). Recovery systems based on turbogenerators can be highly useful and profitable for application in small scale and distributed power generation. The profit is obvious for remote areas without access to centralized power supply and strongly dependent on fuel deliveries which in some cases are carried out by water and air transport, thus significantly increasing their cost.

At present the studies in the field of portable efficient systems of EG recovery are very urgent since they allow to decrease fuel consumption, to increase efficiency, thus reducing the cost of generated electric energy.

Simulation demonstrates that application of electric turbo compound can be more profitable in comparison with turbo charging system [1]. In addition, application of turbogenerators with the power from 4.6 kWto 9.3 kW in internal combustion engine (ICE) installed in a vehicle reduces fuel consumption from 1.33% to 2.76%, respectively [2].

Turbogenerator efficiency is confirmed by direct comparison under conditions of various driving cycles. For instance, when a turbogenerator is installed in parallel with turbo compressor on basic petrol ICE, fuel consumption is reduced by 1.86% and 4.74% for FTP75 and US06 driving cycles, respectively [3].

This work is aimed at development of turbo generator model intended for installation in gas exhaust system of ICE in order to recover EG residual energy for power generation as well as to decrease fuel consumption and specific harmful emissions. The formulated targets will be achieved by computational analysis of turbogenerator3D model based on computational fluid dynamics (CFD simulation).

1.1 Design of Turbogenerator Model

On the basis of computations [4], turbogenerator 3D model was developed. Figure 1 illustrates a longitudinal cross section of the turbogenerator 3D model showing applied design and layout solutions.

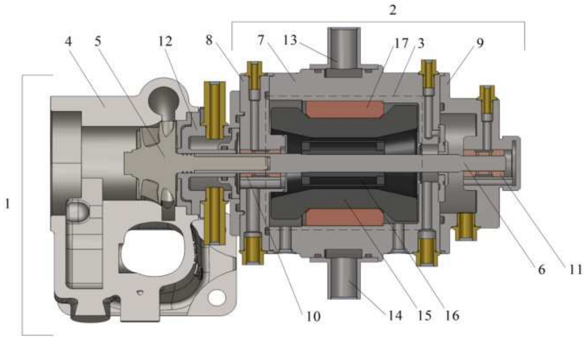

Figure 1: Turbogenerator 3D model

The turbogenerator is comprised of the turbine 1, the casing 2, and the electric machine 3.

The turbine 1of the turbogenerator model is comprised of the turbine casing 4 connected with the model casing 2and the turbine wheel 5 installed on the turbogenerator shaft 6.

The model casing 2is made of steel and comprised of the central part 7, the front 8and the rear 9covers with the slider bearings 10 and 11, the front cooling bush 12, and the coolant inlet 13and outlet 14fittings.

The electric machine 3of the turbogenerator model is comprised of the stator 15 fixed in the turbogenerator casing 2 and the rotor 16 installed on the turbine shaft bush. In the area of the stator windings 17temperature sensors are installed for monitoring of thermal state.

The turbogenerator model is equipped with liquid cooling system comprised of two cavities:

- the front cooling cavity comprised near the turbine and intended for cooling of the casing and the front bearing of the model;
- the cooling cavity of the stator of electric machine.

The lubrication system of the turbogenerator model intended for forced lubrication of the bearings 10and 11of the turbogenerator rotor is hydraulically connected with the ICE lubrication system and is equipped with automatic adjustment of oil temperature.

The main variables of turbogenerator model are summarized in Table 1.

Table 1: Variables of Turbogenerator Model

Parameter	Turbogenerator Model (variant No. 1)
Weight of assembled rotor, g	462.8
Moment of inertia of assembled rotor, $g \cdot mm^2$	51,574.2
Rotor RMP	100,000
Number of blades of turbine wheel	12
Outer diameter of turbine wheel, mm	56
Blade height of turbine wheel, mm	15
Heat exchange surface area of stator on the side of coolant, m^2	0.0101

The developed turbogenerator3D model is used for CFD simulation aiming at verification of the applied solutions, acquisition of detailed data on EG flow, determination of electric power and temperature field of components of the turbogenerator model.

2. METHODS

The procedure of development of turbogenerator model is comprised of computation of gas dynamic processes occurring in turbine wheel space and simulation of heat exchange processes in the cooling circuit of the electric machine.

Computation analysis of the turbogenerator model aimed at determination of main operating variables are performed using Solid Works Flow Simulation software equipped with all required libraries. Capabilities of CFD simulation make it possible to obtain data array with the required model variables as well as to reveal regions and elements of the model which should be improved.

Reasonability of CFD simulation for development of the turbogenerator model is confirmed by significant scope of investigations of radial inflow turbines based on CFD simulations available in publications.

Simulation of EG flow in steady state and analysis of influence of orifice with blades on turbine properties are presented in the work devoted to computation of turbine for automobile turbine compressor [5]. The work [6] discusses configuration of turbine wheel using CFD simulation. In order to optimize computation resources for prediction of EG radial flows, it is possible to apply independent local network [7].

Numerous works are devoted to liquid cooling of electric machines. CFD simulation is applied for analysis of coolant flow in the cooling circuit of electric motor, in addition, hot regions are detected [8, 9].

In order to develop and to fabricate turbogenerator model, the present work applies CFD simulation of gas dynamic processes in turbine which can determine turbine wheel RPM and torque on the turbogenerator shaft. On the basis of the obtained torque and RPM, the power of turbogenerator is computed. The electric power of turbogenerator and heat loss to ICE cooling systems are determined with consideration for efficiency of electric machine.

The present work also discusses CFD simulation of thermal physical processes in the turbogenerator model comprised of gas dynamic processes in turbine and computation of heat exchange processes between solid state element of the model and three heat exchange agents (EG, coolant, and motor oil).

Development and fabrication of turbogenerator model are based on consecutive CFD simulation of two variants of turbogenerator model. After analysis of the obtained values and detection of drawbacks, the design of turbogenerator model (variant No. 1) Is improved as required, thus obtaining turbogenerator3D model (variant No. 2). On the basis of CFD simulation of turbogenerator model (variant No. 2), the final design is determined possessing the required operating variables.

CFD simulation is performed on the basis of computed turbogenerator3D model with modifications aimed at elimination of functionally unused elements and the following assumptions are made:

- Heat exchange between all components of turbogenerator model is ideal;
- Ambient air temperature is constant equaling to 20°C;
- Thermal power on the side of stator windings is distributed uniformly across all windings.

The initial data of turbogenerator model are summarized in Table 2.

Table 2: Initial Conditions of CFD Simulation of Turbogenerator Model

Variable	Value
EGflow rate via turbine, kg/s	0.1
EGtemperature at turbine input,°C	800
Coolant temperature at input to front cooling cavity and to stator of electric machine,°C	60
Coolant flow rate via front cooling cavity, kg/s	0.02
Coolant flow rate via stator of electric machine, kg/s	0.2
Motor oil temperature at input to model,°C	85
Motor oil flow rate via model, kg/s	0.03

The maximum temperature of stator windings is assumed to be 85°C. Primary value of heat power N_{heat} was determined on the basis of previously obtained data [4]. Then, after the first CFD simulation, N_{heat} was adjusted and computations were repeated.

Figure 2 illustrates the motion direction of three heat exchange agents via the turbogenerator models: No. 1 and No. 2 –coolant inlet and outlet; No. 3, No. 4, and No. 5 – motor oil inlet and outlet.

The holes K1 and K2 are used for motor oil drainage, and in the present computations for air ventilation of internal space of electric machine.

In order to increase the number of measured variables, the computation model was supplemented with four cross sections in the turbine wheel space: «In» - turbine inlet; «Or» - orifice; «T» - turbine wheel outlet; «Out» - turbine outlet.

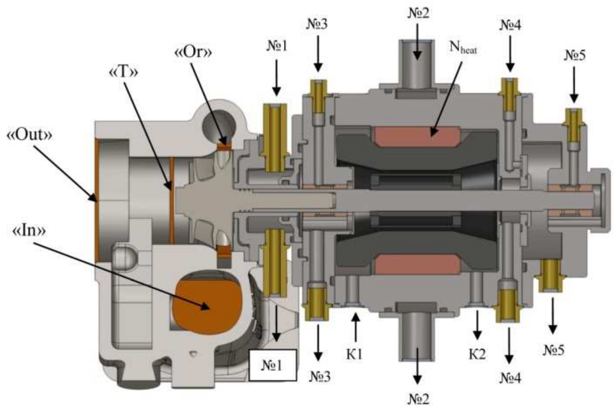

Figure 2: Schematic View of Flows of Three Coolants via Turbogenerator Model and Positions of Reference Sections in Turbine Wheel Space

3. RESULTS

During CFD simulation of both variants of the turbogenerator model the energy variables of turbine and cooling system of electric machine stator were determined. The obtained results are summarized in Table 3.

3.1 Turbogenerator Model (Variant No. 1)

Analysis of the turbogenerator model (variant No. 1) revealed some drawbacks related with insufficient performance of the turbine and cooling system of electric machine. The revealed drawbacks made it possible to determine possible improvements of operating variables of the turbine and cooling system of electric machine.

Electric power of the turbogenerator model was 9.81 kW, which was lower than the required 10 kWindicating at necessity to increase turbine wheel RPM and torque on turbine shaft. This could be achieved by optimization of turbine wheel design, for instance, by decrease in the number of turbine wheel blades. This approach can be substantiated by peculiarities of interaction between EG flow and turbine wheel blades. Accordingly, upon decrease in the number of turbine wheel blades, the quality of interaction between EG flow and blades improves.

As a consequence of CFD simulation it was revealed that the performances of cooling systems should be improved, since the maximum temperature of stator windings achieved 92.8°C. This can be attributed to insufficient cooling efficiency of stator of electric machine upon its operation at maximum capacity which leads to overheating of stator windings. Therefore, it is required to search for technical solutions capable to provide operation of stator windings in the required temperature range up to 85°C.

3.2 Turbogenerator Model (variant No. 2)

The following modifications were added to the design of turbogenerator model (variant No. 2) developed on the basis of turbogenerator model (variant No. 1) aiming at elimination of the revealed drawbacks:

- the number of turbine wheel blades were decreased from 12 to 10;
- configuration of cooling cavity of electric machine was modified, thus increasing the stator heat exchange surface area on the side of coolant by 2.2 times reaching 0.0225 m^2;
- -the design provided direct contact between coolant and surface of stator windings.

The modifications applied to the design of stator of electric machine aiming at increase in cooling efficiency of stator windings are illustrated below in Figures 3 and 4.

Heating of the solid-state elements of turbogenerator model is estimated visually by means of diagrams of temperature distribution in axial longitudinal cross section of the model. Taking into account high temperature gradient along the model, it was separated into two independent areas, each with individual temperature scale.

Figures 3 and 4 illustrate temperature distribution of solid-state elements of turbogenerator models (variant No. 1 and No. 2) in their axial longitudinal cross sections.

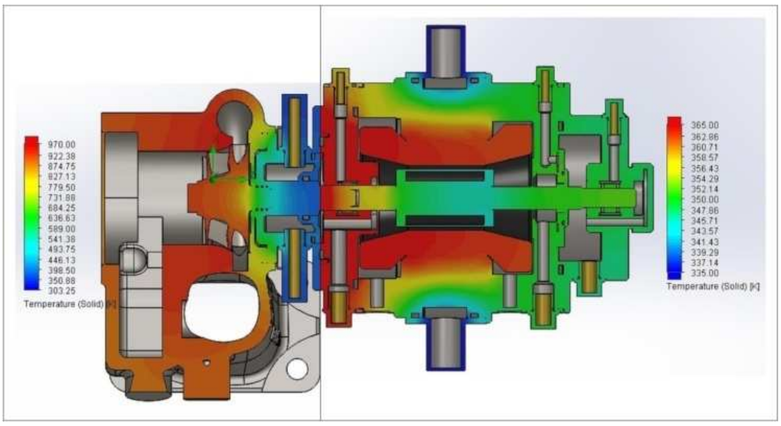

Figure 3: Temperature Distribution of Solid-State Elements of Turbogenerator Model (Variant No. 1).

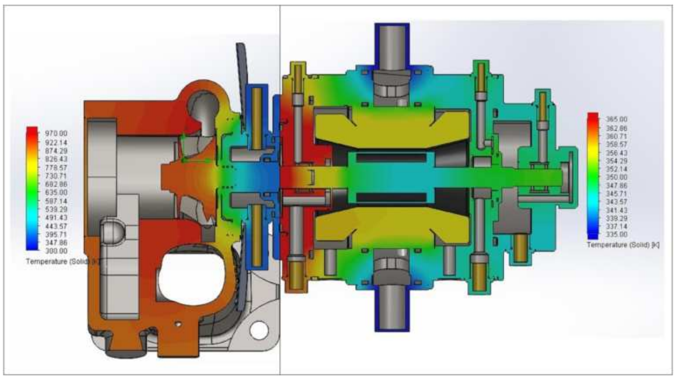

Figure 4: Temperature Distribution of Solid-State Elements of Turbogenerator Model (Variant No. 2)

According to Figures 3and 4, modification of turbine wheel design does not affect total turbine temperature mode. Modifications applied to the design of stator of electric machine (variant No. 2)in order to improve cooling efficiency of stator windings provided temperature decrease of windings. In both variants of turbogenerator model the temperatures of shaft, rotor of electric machine and bearing are in operation range.

Table 3 summarizes variables of turbogenerator models (variant No. 1 and No. 2) obtained by CFD simulation.

Table 3: Specifications of Turbogenerator Models (variant No. 1 and No. 2)

Variable	Turbogenerator Model (Variant No. 1)	Turbogenerator Model (Variant No. 2)
Number of blades of turbine wheel	12	10
Turbine wheel RPM	102,965	107,471
Torque on turbine shaft, N·m	0.958	1.029
Power on turbine shaft, kW	10.33	11.58
Power of electric machine, kW	9.81	11 (10.7regulated)
Thermal power released in turbogenerator electric machine, kW	0.517	0.579 (0.535 regulated)
Coolant temperature at input/output from electric machine,°C	60/60.65	60/60.75 (60.7 regulated)
Maximum temperature of stator windings,°C	92.8	88.1 (84.6 regulated)

According to the obtained data of turbogenerator model (variant No. 2), it was established that the generated electric power of 11 kW exceeded the rated value of 10 kW. This leads to increased heat loss in electric machine and heating of stator windings to 88.1°C which does not comply with the preset ultimate value of 85°C.

In order to solve this problem, the electric machine was regulated with restriction of the generated electric power at the level of 10.7 kW. As a consequence, the heat loss in electric machine decreased to 0.535 kW and the maximum temperature of stator windings was 84.6°C. All values acquired with consideration for the regulation of electric machine are given in brackets in Table 3.

Figure 5 illustrates electric power generated by turbogenerator models (variant No. 1 and No. 2)as a function of EG temperature at constant EG flow rate across the turbine. Curves «No. 1» and «No. 2» correspond to the variables of turbogenerator models, variant No. 1 and variant No. 2, respectively. The curve «No. 2, reg.» shows variation of electric power upon regulation of electric machine.

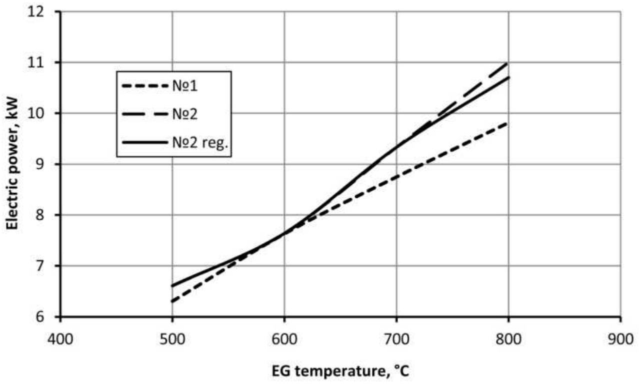

Figure 5: Electric Power Generated by Turbogenerator Models (Variants No. 1 and No. 2) as a Function of Temperature

According to CFD simulation of turbogenerator model and adjustment of its design aiming at enhancement of turbogenerator performances and the required cooling of electric machine, the turbogenerator model was fabricated (Figure 6) including all technical solutions used in the turbogenerator model (variant No. 2).

Figure 6: Turbogenerator Model

4. DISCUSSIONS

This article discusses in brief computations of turbogenerator model using CFD simulation as well as the computation results. Besides, turbogenerator model is described showing positions and interaction of main elements of the model.

The results of computation analysis of the turbogenerator model are of practical usefulness and can be applied for subsequent projects related, for instance, with experimental studies.

The obtained data demonstrate reasonability of application of turbogenerator model as a component of EG energy recovery systems which can be useful and profitable in the facilities of small scale and distributed power generation.

During the analysis the influence of the number of turbine wheel blades on energetic performances of the turbine was established. On the basis of the obtained results, the turbine wheel with 10 blades provides higher performances in comparison with those of turbine wheel with 12 blades. In order to explain this feature, this work made the assumption according to which the decrease in the number of blades improved the quality of interaction between EG flow and blades.

The issue of cooling of electric machine is highly important since its stator is directly connected to the turbine casing, and the turbine wheel together with generator armature form single rotary unit. As a consequence, there occurs heat flow towards the components with lower temperature. In addition, heat is released during operation of electric machine, this can lead to overheating of stator windings.

While determining variables of cooling system, it was established that the increase in power of electric machine led to increase in thermal power released during operation, and this could lead to overheating of stator windings. Such overheating could be prevented by modifications in cooling cavity design located in stator, and by adjustments of coolant flow rate and temperature.

Cooling efficiency of electric machine could be reasonably improved by decrease in coolant temperature at stator inlet, for instance, from 60 to 50°C. However, in this case dissipation of heat power to ambient environment becomes more complicated since temperature gradient decreases. Thus, at constant ambient temperature equaling to 20°C the most efficient is the combination where coolant temperature equals to 60°C.

Therefore, in order to solve the issue of electric machine cooling, a compromise solution is required based on design peculiarities of operation modes of cooling systems and overall turbogenerator.

5. CONCLUSIONS

As a consequence of activities comprised of development of turbogenerator 3D model based on analytical and numerical studies performed at previous stage and subsequent CFD simulation, the turbogenerator model was developed.

CFD simulation of turbogenerator3D model was comprised of successive analysis of two variants. As a consequence of the simulation (variant No. 1), it was detected that the generated electric power was insufficient equaling to 9.81 kW and the stator windings were heated to 92.8°C which did not conform to preset ultimate operating temperature of 85°Cevidencing overheating.

In order to eliminate the detected drawbacks, modifications to the design were proposed on the basis of which improved turbogenerator 3D model was developed (variant No. 2). As a consequence of CFD simulation of the obtained 3D model as well as with consideration for adjustment of generated electric power, the value of 10.7 kW was achieved. Herewith, the maximum temperature of stator windings of electric machine was 84.6°C.

As a consequence of CFD simulation, the turbogenerator 3D model was approved and fabricated. Further research of turbogenerator model is comprised of experimental studies, the results will be presented in subsequent publications.

6. ACKNOWLEDGEMENTS

This work was supported by the Ministry of Science and Higher Education of the Russian Federation, agreement No. 14.574.21.0154 of September 26, 2017. Unique identifier of applied scientific research: RFMEFI57417X0154.

REFERENCES

1. *Mohd Noor, A., ChePuten, R., RajOo, S., Basheer, U. M., MdSah, M. H., Shaikh Salleh, S. H. 2015. Simulation Study on Electric Turbo-Compound (ETC) for Thermal Energy Recovery in Turbocharged Internal Combustion Engine. Applied Mechanics and Materials. 799-800. 10.4028/www.scientific.net/AMM.799-800.895.*

2. *Briggs, I., McCullough, G., Spence, S., Douglas, R., O'Shaughnessy, R., Hanna, A., Rouaud, C., Seaman, R. 2013. A Parametric Study of an Exhaust Recovery Turbogenerator on a Diesel-Electric Hybrid Bus. Proceedings of the ASME Turbo Expo. 5. 10.1115/GT2013-94492*

3. *Zhuge, W., Huang, L., Wei, W., Zhang, Y., He, Y. 2011. Optimization of an Electric Turbo Compounding System for Gasoline Engine Exhaust Energy Recovery. SAE Technical Papers. 10.4271/2011-01-0377.*

4. *Lezhnev, L. Yu., Tatarnikov, A. P., Skvortsov, A. A., Papkin, I. A., Nekrasov, A. S. 2018. Turbogenerator: Part 1: Simulation. International Journal of Engineering & Technology, 7 (3.15): 277-279. DOI: 10.14419/ijet.v7i3.15.18688.*

5. *Jawad, L. H. 2018. Numerical Prediction of a Radial Turbine Performance Designed for Automotive engines Turbocharger. Journal of University of Babylon, Engineering Sciences, Vol.(26), No.(4): 132-145.*

6. *Mohammad, M. M., Mohan, A. A., Habeeb, A. H. 2018. Improving and analysis turbine wheel of turbocharger for high-performance engines. (2018). Journal of Mechanical Engineering Research and Developments 41(3):91-96. DOI: 10.26480/jmerd.03.2018.91.96.*

7. *Galindo, J., Hoyas, S., Fajardo, P., Navarro, R. 2013. Set-Up Analysis and Optimization of CFD Simulations for Radial Turbines. Engineering Applications of Computational Fluid Mechanics Volume 7, Issue 4. https://doi.org/10.1080/19942060.2013.11015484.*

8. *Pechánek, R., Bouzek, L. 2012. Analyzing of Two Types Water Cooling Electric Motors Using Computational Fluid Dynamics. 15th International Power Electronics and Motion Control Conference and Exposition, EPE-PEMC 2012 ECCE Europe. DOI: 10.1109/EPEPEMC.2012.6397424.*

9. *Iqbal, Z., & Lodhi, S. Noise Pollution Caused by Electric Generators and Firing Outside Marriage Halls in Lahore: A Sensitivity Analysis using Contingent Valuation.*

10. *Borges, S. S., Cezario, C. A., Kunz, T. T. 2008. Design of water cooled electric motors using CFD and thermography techniques. 18th International Conference on Electrical Machines, pp. 1-6. doi: 10.1109/ICELMACH.2008.4800078.*